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BALLISTIC PROPERTIES OF COMPOSITE MATERIALS
FOR PERSONNEL PROTECTION

J. R. BROWN and G. T. EGGLESTONE

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**BALLISTIC PROPERTIES OF COMPOSITE MATERIALS
FOR PERSONNEL PROTECTION**

J.R. Brown and G.T. Egglestone

MRL Technical Report
MRL-TR-89-6

ABSTRACT

The Australian Army currently has requirements for new combat and vehicle crewman helmets. Various polymer materials in the form of fibre-reinforced organic matrix composites have been shown to have sufficient resistance to ballistic impact to be regarded as attractive construction materials for personnel protective helmets. This report discusses the relative ballistic properties of those organic matrix composite materials which are considered as prime candidates to meet the requirements of the Army's new combat and vehicle crewman helmets.

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Jim Brown graduated in Physical Chemistry BSc (Hons) from the University of Queensland in 1966. He was awarded a PhD in 1970 from the same University for research into high-energy radiation effects on polysulfone polymers. In the same year he joined MRL where he has been involved in research in a number of organic material technology areas such as thermal properties and fire hazards, high performance fibres, high-energy laser effects, chemical survivability, lightweight ballistic protection and properties of advanced composites. During 1984-85, Dr Brown was attached to the US Army Materials Technology Laboratory (AMTL) in Watertown, Massachusetts, where his work was concerned with the application of organic composite material systems as structural armour in lightweight military platforms.



Graeme T. Egglestone has been employed at Materials Research Laboratory since 1988. He graduated with a Diploma of Applied Science from FIT in 1975. He has extensive experience in the area of degradation and ballistic performance of polymeric materials and composites. He has works published both nationally and internationally in these fields. In 1986-1987 he was seconded to the US Natick Research Development and Engineering Center in Massachusetts where he continued research into the ballistic response of fibrous materials and composites.

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BALLISTIC PROPERTIES OF COMPOSITE MATERIALS FOR PERSONNEL PROTECTION

1. INTRODUCTION

There is an array of ballistic threats which the soldier and combat vehicle crewman encounter on the battlefield. These include fragmenting munitions from tank guns, rocket launchers, field guns, howitzers and mortars as well as rifled ammunition and more advanced ballistic threats. Effective ballistic protection of the individual soldier is thus of prime concern and clearly must take into account the most likely threats as well as any operational constraints which protective armour might impose. In addition, it must be recognized that many scenarios will require the incorporation of ballistic materials with other protective materials to provide an integrated protective system. Recent reports (1-3) show that fragmentation weapons are the major threat to soldiers on the battlefield, and account for 60-80% of casualties. These weapons produce large numbers of small hardened steel or cast iron fragments by both natural and controlled fragmentation processes. A large percentage of the fragments weigh less than one gram and initial velocities can be in the vicinity of 2000 m/s (1). It is clearly desirable that personnel armour systems are designed to meet this type of threat.

With advances in the destructive nature of fragmentation weaponry, existing individual ballistic protection is widely considered to be inadequate. The United States, British and Israeli Armies are now largely equipped with new composite combat helmets (2,4) manufactured from advanced fibres and specially selected resins offering lighter weight and/or greater protection. Spain and Canada have embarked on new combat helmet procurement programs, and research and development in the Federal Republic of Germany and other NATO countries are soon likely to lead to the introduction of new composite combat helmets. The Australian Army has also recognized the need to replace its conventional steel combat helmet as well as its current vehicle crewman helmet with new units offering higher ballistic protection as well as other specified design and compatibility requirements. Army Staff Requirements (ASR's) have been issued for both types of helmet. In this report, the relative ballistic properties of those organic matrix composite materials which are considered as prime candidates to meet the requirements of the Army's new combat and vehicle crewman helmets are discussed.

2. CURRENTLY USED COMBAT HELMETS

2.1 Australia

The current combat helmet used by the Australian Army is similar to the M-1 steel helmet used by the United States Army prior to 1982. It consists of a Hadfield manganese-type steel shell and a reinforced nylon liner (5). The latter is made up of four layers of ballistic grade nylon impregnated with a phenolformaldehyde/poly(vinyl butyral) resin (5). The helmet weighs 1.37 kg and has a V_{50} value of 402 m/s against a 1.10 g fragment simulating projectile (FSP) (8). The V_{50} value is defined as the projectile velocity at which the probability of penetration of the target is 50% (7), and is determined by the procedures of MIL-STD-882E (7,8).

2.2 United Kingdom

The British Army has recently introduced into service a new GS Mk 6 combat helmet. This helmet consists of an outer shell of ballistic nylon laminated with approximately 20% by weight of a 50% mixture of phenolformaldehyde and poly(vinyl butyral) resins. The shell is made up of 23 layers of 290 g/m² plain weave nylon 6,6 textile, with a total areal density of 7.7 kg/m² and weight of 1.0 kg for the medium size. The GS Mk 6 also has an impact absorbing liner of high density polyethylene foam (total helmet weight-medium is 1.3 kg). The V_{50} value for a 1.10 g FSP is 415 m/s.

2.3 United States

In 1982 the United States Army introduced an integrated personnel protective system referred to as PASGT - Personal Armor System Ground Troops, which consists of an aramid protective vest and an aramid fibre-reinforced composite combat helmet. The aramid selected for the helmet was a 460 g/m² scoured Kevlar 29 fabric (19 layers) in a 2 x 2 basket weave from 1500 denier yarn. The resin is similar to that used in the British Army's GS Mk 6 helmet, and is present at approximately 18-20% by weight. This results in a shell areal density of 10.8 kg/m² and a weight of 1.25 kg for the medium size. The total helmet weight-medium is 1.45 kg. The V_{50} value of the PASGT helmet for a 1.10 g FSP is 610 m/s.

The ballistic properties of combat helmets currently used by the Armies of Australia, the United Kingdom and the United States are summarized in Table 1.

3. BALLISTIC PROPERTIES OF COMPOSITE MATERIALS

The efficiency of a material in defeating a high speed projectile clearly relates to its energy absorbing properties at very high strain rates (10^3 - 10^5 s⁻¹), and to the amount of material which is involved in the energy absorbing process. The former is governed by the area under the material stress/strain curve. Since molecular mechanisms which may allow large elongations at low strain rates are largely inoperative at ballistic strain rates, strain at failure is low and high energy absorption is dependent on high material strength. The amount of material involved in the energy absorbing process is governed by the sonic

velocity of the shock wave emanating from the point of impact, which in turn is related directly to the material modulus, and indirectly to its density (9,10).

Those materials which have high moduli and high strengths, particularly on a weight basis, ie. specific values, are the organic and inorganic fibres such as glass, aramid and polyethylene. This is illustrated in Figure 1. The behaviour of a fibre or yarn when impacted by a projectile is shown in Figure 2. A longitudinal wave propagates from the point of impact along the fibre at the speed of sound in the material, C , which is given by (9,10):

$$C = \sqrt{E/\rho} \quad (1)$$

where E is the fibre tensile modulus (Young's modulus) and ρ the density. Behind this longitudinal wave, material flows towards the impact point at constant tensile strain, ϵ_0 , which can be shown to be related to the impact velocity, V , (10) by

$$V = C(\epsilon_0 [2 \sqrt{\epsilon_0 (1 + \epsilon_0)} - \epsilon_0])^{1/2} \quad (2)$$

A second wave propagates along the fibre behind which material begins to move transverse to the fibre axis parallel to and at the velocity of the projectile. The velocity of the transverse wave, U , is related to the strain and the strain wave velocity (10) by

$$U = C(\sqrt{\epsilon_0 (1 + \epsilon_0)} - \epsilon_0) \quad (3)$$

The transverse wave velocity is generally much lower than the longitudinal velocity.

The mechanisms controlling the high velocity impact properties of composite systems are not clearly understood. While some mathematical models describe adequately the behaviour of fibres or yarns and idealised fabric systems on ballistic impact, none have yet been developed to the extent where real fabric systems can be optimized in terms of materials, design and fabrication procedures. The essential difference between the behaviour of a yarn and a fabric is due to yarn crossovers. Reflections and diversions (see Figure 3) attenuate the magnitude of the wave front while progressively increasing the strain in the material behind the wave front. The impact point is always the point of maximum strain and penetration occurs when the strain exceeds the dynamic fracture strain of the material. The rate of strain increase is a complex function of wave velocity (fibre tensile modulus), impact velocity, fabric geometry, as well as other textile surface properties such as inter yarn friction.

Transient deformation on ballistic impact is minimized by incorporating a suitable thermosetting, thermoplastic or elastomeric resin matrix to form a composite material. At ballistic strain rates, molecular mechanisms which allow the matrix to act as a stress transfer medium under quasi-static loading conditions are only partially applicable, and the principal effect of the matrix resin is to bond yarn crossovers. This results in higher wave front reflection and thus enhanced stress concentration at the impact point, and inferior ballistic performance. Nevertheless, minimum transient deformation is of paramount importance in some ballistic applications e.g. military combat helmets and vehicle spill liners. In these applications structural integrity is an additional requirement

to ballistic protection. Thus resin systems which can be used to fabricate composites with optimum ballistic properties and minimum transient deformation as well as other desirable mechanical properties are important considerations for these particular applications.

4. CANDIDATE HELMET MATERIALS

Nylon has been used in personnel armour systems for many years, but has now largely been replaced by aramids which offer superior ballistic performance in both fibrous (soft armour) and composite (hard armour) forms (11,12). Recently a new class of high performance fibre has been developed which has been shown to have impressive ballistic properties and hence considerable potential in personnel armour applications (13-16). This is an extended chain polyethylene marketed in the USA by Allied-Signal Corporation as Spectra 900 or 1000, and in The Netherlands and Japan by DSM Research and Toyobo respectively as Dyneema. Two further heterocyclic fibres, poly(p-phenylene benzobisthiazole) (PBT) and poly(p-phenylene benzobisoxazole) (PBO), currently being developed by the United States Air Force and Du Pont, and Dow respectively, also have potential as ballistic protective materials (16). However, PBT and PBO fibres are not expected to be available commercially for five to ten years.

The physical properties of the candidate ballistic fibres under quasi-static loading conditions are given in Table 2 (16). Table 3 shows similar properties generated from single yarn impact data at 305 m/s, i.e. at a ballistic strain rate (16). The newer fibres have strength, modulus and strain wave velocity values in excess of those of Kevlar 29 aramid and nylon, with elongation at break values less than Kevlar and nylon. These properties all suggest potential for substantial improvement in ballistic resistance capabilities which has been recently demonstrated in the case of Spectra polyethylene (13,15). Polyethylene also has the additional advantage of a significantly lower density and thus the potential for use as lighter personnel armour. Evidence of fibre fusion at the point of rupture on ballistic evaluation of nylon (12,16) has led to the suggestion that high thermal stability is a necessary fibre prerequisite for enhanced ballistic performance. However, the superior properties of extended chain polyethylene, which has an even lower melting point (Table 2), demonstrates that thermal stability is not a critical factor in ballistic resistance.

Numerous ballistic tests conducted by Tobin at the Stores and Clothing Research and Development Establishment (SCRDE), Essex, UK, using FSP's of various sizes, have shown that for a wide range of composite materials, V_{50} and areal density are related empirically by the expression

$$V_{50} = K A^{0.5} \quad (4)$$

where A is the areal density and K is a constant for a particular target material and FSP (17). The data clearly illustrate the superior ballistic performance of composites containing aramid fibres over those containing nylon fibres, which increases progressively with fragment size. For nylon and Kevlar aramid composite helmet materials, K values for 1.10 g FSP's are 149.8 and 193.8 respectively, with V_{50} in m/s and areal density in kg/m^2 . The V_{50} - areal density data of Merriman and Miner (18) for Kevlar 29 aramid composites and 1.10 g FSP's can also be shown to fit the above empirical relationship with an identical material constant ($K = 193.8$). There are also limited V_{50} - areal density ballistic data for

Spectra polyethylene composites using 1.10 g FSP's. The data of Merriman and Miner (13) fit equation (4) with $K = 219.5$ for Spectra polyethylene/polyester composites, while similar data published by Allied Signal Corporation for Spectra/thermoplastic resin latex composites also fit equation (4) with $K = 236.5$. From plots of V_{50} versus areal density (Figure 4), V_{50} values for these materials at any particular areal density can be compared. In making these comparisons, the different resin matrices and fibre contents of the various composite materials should be noted. The SCRDE aramid composites (17) and those of Merriman and Miner (13) contain 18% and 20% by weight respectively of a polyester or a phenolformaldehyde-poly(vinyl butyral) resin, and no significant difference in the ballistic properties can be identified. However, the low thermoplastic resin latex content (10% by weight) of the Allied Signal polyethylene composites elevates significantly the ballistic performance above that observed by Merriman and Miner for polyethylene/polyester composites with a higher resin content (25% by weight).

From Figure 4, the levels of ballistic protection offered by nylon, aramid and polyethylene composite helmet shells can be estimated. For an areal density of 7.7 kg/m^2 , which corresponds to that of the UK GS Mk 6 composite helmet shell, nylon, aramid and polyethylene have V_{50} values of 415, 540 and 610-650 m/s respectively. For an areal density of 10.8 kg/m^2 , which equivalent to that of the US PASGT composite helmet shell, nylon, aramid and polyethylene have V_{50} values of 490, 630 and 720-770 m/s respectively. Alternatively, for a specific V_{50} value, eg. 600 m/s, the corresponding areal densities of composite shells of nylon, aramid and polyethylene are 16.2, 9.8 and 6.5-7.5 kg/m^2 respectively. These areal densities correspond to medium size helmet shell weights of $2.0 \pm 0.1 \text{ kg}$ (nylon), $1.20 \pm 0.07 \text{ kg}$ (aramid) and $0.85 \pm 0.10 \text{ kg}$ (polyethylene) depending on the design cover factor of the helmet.

One of the most suitable resin systems used in composites for ballistic protection is a blend of phenolformaldehyde and poly(vinyl butyral) (PF/PVB) resins, usually in equal parts by weight. This system is used as the matrix in the US PASGT and the UK GS Mk 6 combat helmets. The presence of the PVB results in a toughened composite which has been shown to be equivalent ballistically to those containing polyester or vinyl ester matrices (13,17), and superior to those containing epoxy matrices (11). The ballistic properties of PF/PVB - aramid composites does not change significantly as the PVB content of the resin mixture is varied from 20 to 80% (18). However, approximately equal parts by weight have been used because of advantageous structural integrity considerations such as low velocity impact resistance and low transient deformation on ballistic impact.

The PF/PVB resin system is readily applied to fabric reinforcement material and "B staged" into a prepreg, which in turn can be rapidly cured at elevated temperature, eg. 180°C for 10 minutes, and moderate pressure into a ballistic composite. Such conditions are suited to the fabrication of aramid and nylon reinforced composites, but not for polyethylene reinforced composites because of the low fibre melting point (Table 2). The ballistic properties of Spectra polyethylene laminates are not significantly affected by exposure to temperatures up to 120°C (16), and initial experiments show that PF/PVB resin systems can be cured at this temperature although the cure time is necessarily longer (18,19). A more efficient crosslinking accelerator system may allow appreciable reductions in cure time at 120°C . Other low temperature curing resin systems such as polyurethanes, polyesters, vinyl esters and styrene-butadiene elastomers are currently being evaluated as suitable matrices for polyethylene fibre ballistic composites.

5. CONCLUSIONS

Materials currently used in the combat helmets of the Australian, United States and British Armies and their respective ballistic resistances have been outlined, and the ballistic properties of advanced fibre-reinforced organic matrix composites have been reviewed. The performance of state of the art materials has been discussed in terms of the V_{50} ballistic limit for 1.10 g fragment simulating projectiles and material areal density, from which estimates can be made of the levels of ballistic protection offered by various candidate composite materials for new combat and vehicle crewman helmets required by the Australian Army.

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Table 1 Ballistic Properties of Current Combat Helmets

Helmet	Weight (kg)	Areal Density (kg/m ²)	V ₅₀ (m/s)
Australian M-1			
Steel outer	1.01		299
Liner	0.36		283
Combination	1.37	10.8	402
United Kingdom GS Mk 6	1.3	7.7	415
United States PASGT	1.45	10.8	610

Table 2 Physical Properties of Candidate Helmet Materials

Fibre Type	Density (g/cm ³)	Specific Strength (m x 10 ⁻⁵)	Specific Modulus (m x 10 ⁻⁵)	Elongation (%)	Melting Point (°C)
Nylon 6,6	1.14	0.88	4.05	18.2	254
Kevlar 29	1.44	1.98	47.3	3.6	427
Spectra 1000	0.97	3.24	171	2.8	147
PBT	1.59	2.64	180	1.5	370

Table 3 Physical Properties of Candidate Helmet Materials at Ballistic Strain Rates*

Fibre Type	Specific Strength (m x 10 ⁻⁵)	Specific Modulus (m x 10 ⁻⁵)	Elongation (%)	Strain Wave Velocity (m/s)
Nylon 6,6	0.60	3.87	13.0	2,540
Kevlar 29	1.00	42.8	2.6	6,770
Spectra 1000	2.21	75.6	2.2	8,710
PBT	1.76	99.0	1.4	10,160

* Data generated from single yarn impact tests at 305 m/s (16).

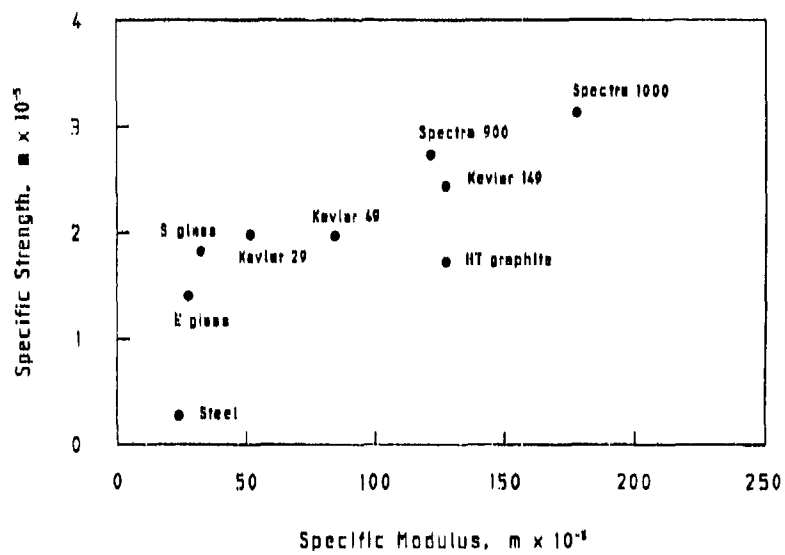


Figure 1 Specific strength and modulus of organic and inorganic reinforcing fibres.

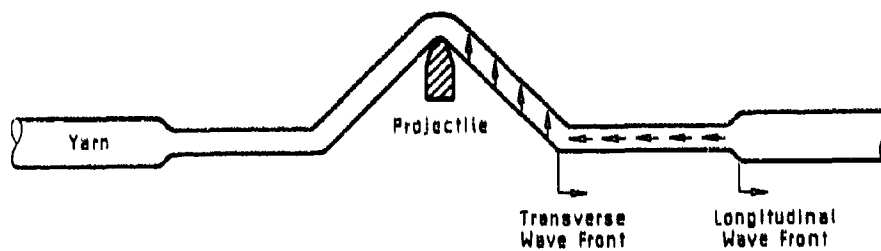


Figure 2 Behaviour of a fibre or yarn on ballistic impact by a projectile.

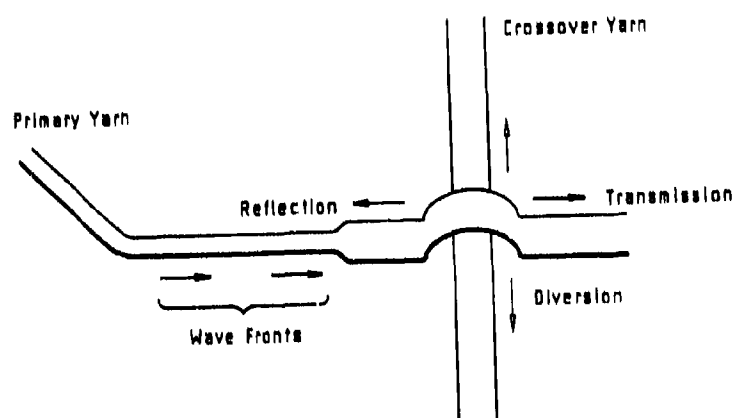


Figure 3 Effect of fibre or yarn crossovers on longitudinal wave front propagation (1).

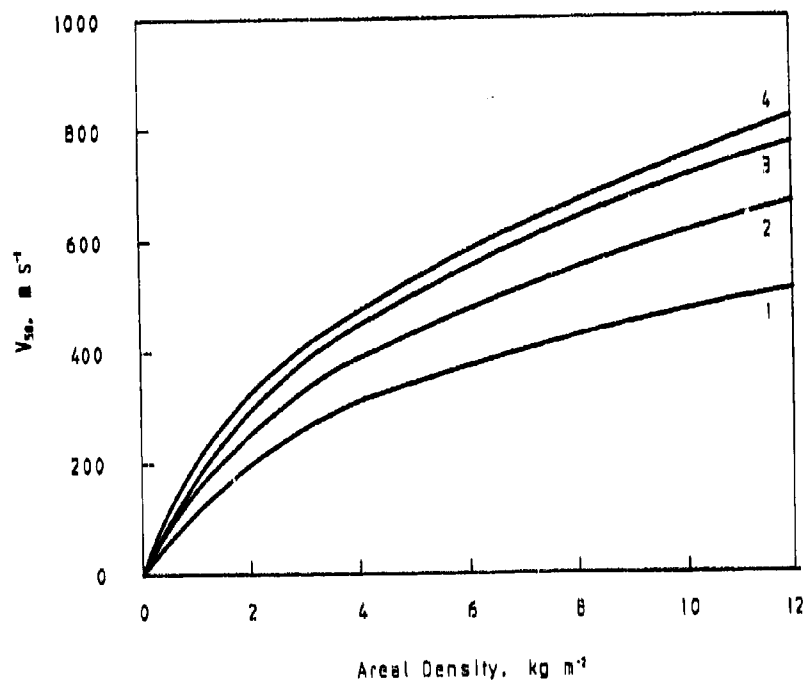


Figure 4 Plots of V_{50} versus areal density for (1) nylon, (2) Kevlar aramid, (3) Spectra polyethylene/polyester and (4) Spectra polyethylene/thermoplastic resin latex composites on ballistic impact by 1.10 g fragment simulating projectiles.

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